

RARE KAON DECAY EXPERIMENTS:

$K \rightarrow \pi \nu \bar{\nu}$ and KOTO Step-2

ELIZABETH WORCESTER, FOR THE LOI AUTHORS

RARE & PRECISION FRONTIER WORKSHOP, RF02, OCTOBER 2, 2020

Measurement of $K_L \rightarrow \pi^0 \nu \bar{\nu}$ at J-PARC: KOTO Step-2

KOTO Collaboration, BNL

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KOTO Step-2 LOI

US Kaon LOI

*US Participation in Current & Future Rare Kaon
Decay Experiments*

Submitted to Rare Processes and Precision Measurements:
Weak decays of strange and light quarks (RF02)

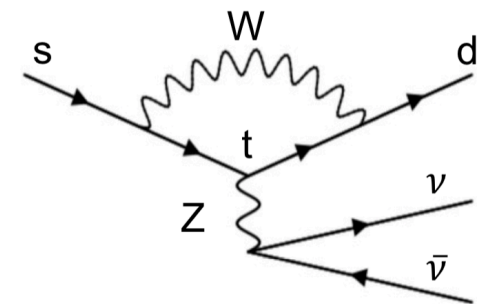
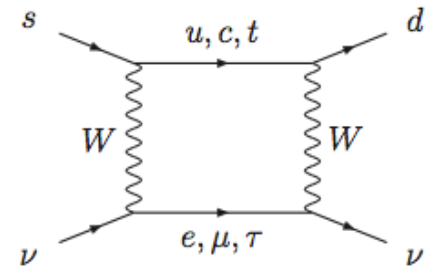
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Authors: Wolfgang Altmannshofer (UC Santa Cruz), Leo Bellantoni (FNAL), Gregory Bock (FNAL), Norman Christ (Columbia U.), David Christian (FNAL), David E. Jaffe (BNL), Douglas Jensen (FNAL), Christopher Kelly (Columbia U.), Steve Kettell (BNL), Andreas Kronfeld (FNAL), Jonathan Lewis (FNAL), Matthew Moulson (INFN Frascati), Hogan Nguyen (FNAL), Ronald Ray (FNAL), Jack Ritchie (U. of Texas), Phil Rubin (George Mason U.), Robert Tschirhart (FNAL), Yau Wah (U. of Chicago), Juliana Whitmore (FNAL), Elizabeth Worcester (BNL), Eric Zimmerman (U. of Colorado)

SCIENTIFIC BACKGROUND & MOTIVATION

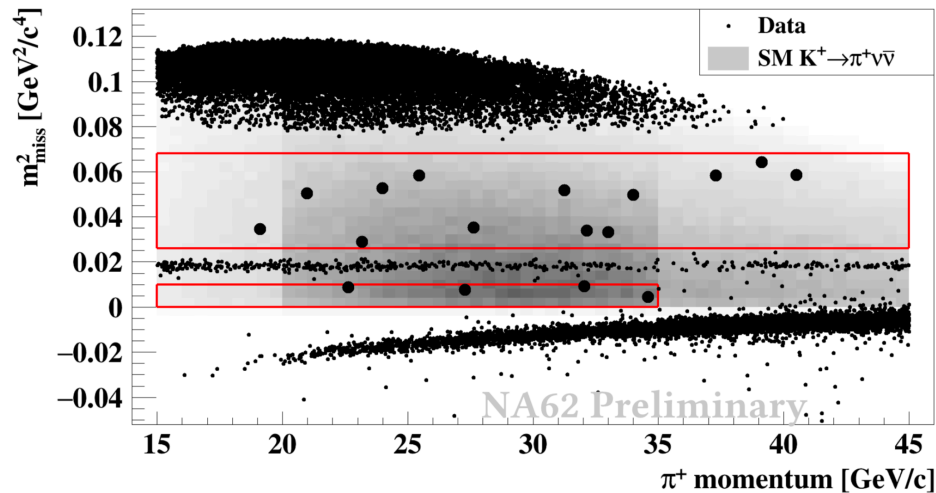
- $K \rightarrow \pi \nu \nu$ decays are excellent probes of new physics
 - Most precisely predicted FCNC decays involving quarks
 - Theoretically clean so clear evidence for new physics if deviation from SM predictions are observed
 - Virtual processes provide information about flavor- and CP-coupling of any new particles
 - Access to effects at energies higher than those directly accessible at the Energy Frontier
- $K^+ \rightarrow \pi^+ \nu \nu$
 - Recently observed by NA62 (CERN), previously observed by E787/949 (BNL)
 - Measured BR (NA62): $(11.0^{+4.0}_{-3.5, \text{stat}} \pm 0.3_{\text{syst}}) \times 10^{-11}$ [ICHEP 2020](#)
 - Theory BR: $(8.4 \pm 1.0) \times 10^{-11}$ [JHEP 11 033 \(2015\)](#)
- $K_L \rightarrow \pi^0 \nu \nu$
 - Branching ratio limit (KOTO): $< 3.0 \times 10^{-9}$ (90% C.L.) [Phys.Rev.Lett. 122 \(2019\) no.2, 021802](#)
 - Grossman-Nir limit from NA62: $\sim 5 \times 10^{-10}$ [ICHEP 2020 \(eyeball\)](#)
 - Theory BR: $(3.4 \pm 0.6) \times 10^{-11}$ [JHEP 11 033 \(2015\)](#)



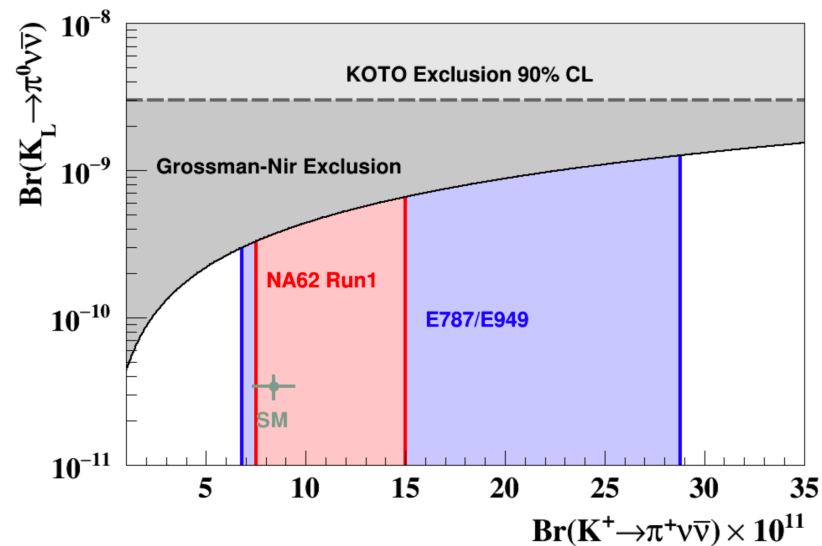
CURRENT EXPERIMENTAL STATUS: NA62

See previous talk by M. Moulson

2018 Data



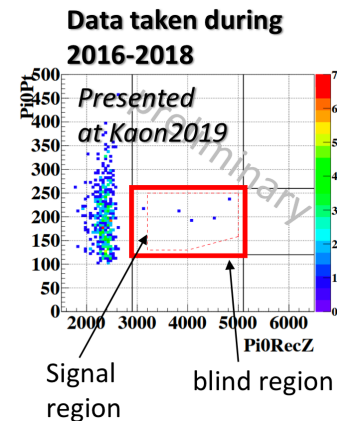
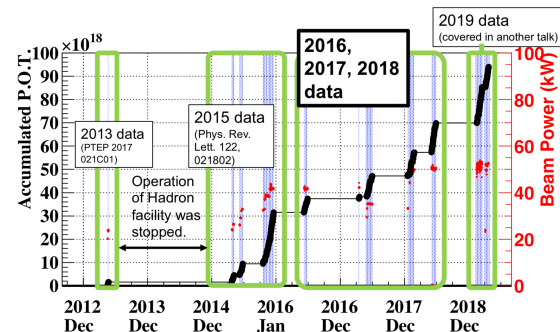
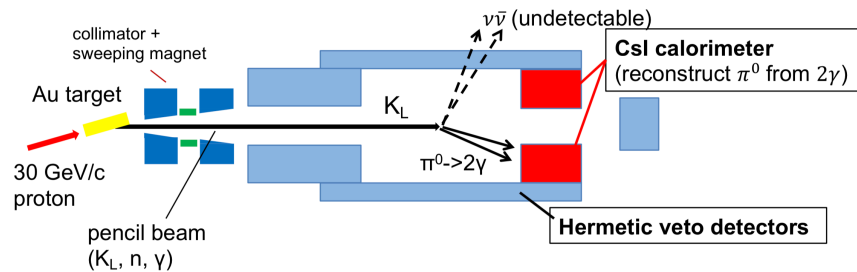
5.3 background + 7.6 SM signal events expected, 17 events observed



CURRENT EXPERIMENTAL STATUS: KOTO

- Limit based on 2015 data: $<3.0 \times 10^{-9}$ (90% C.L.)
 - No events observed in signal region
- Blind analysis of 2016-2018 data yielded 4 events in the signal region (expected $<<1$)
 - One event from mistake in cut application
 - Additional background from charged kaon decay identified: expect ~ 1 event in signal region
 - Upstream detector needed to veto charged kaons
 - Prototype installed for 2020 run
 - Design in progress for higher efficiency UCV
- KOTO Step-I expects to reach Standard Model single event sensitivity by 2025

$$K_L \rightarrow \pi^0 \nu \bar{\nu} : (\pi^0 \rightarrow) 2\gamma + \text{nothing}$$



NEXT GENERATION EXPERIMENTS

- Required to make a precision measurement of $K^+ \rightarrow \pi^+ \nu \nu$ and to make a significant observation of $K_L \rightarrow \pi^0 \nu \nu$
 - Would become a very high priority if hints of new physics emerge from NA62 or KOTO
 - In absence of hints, more precise measurements open doors to potential discovery
- High intensity K^+ and K_L beams at SPS, see previous talk by M. Moulson
- KOTO Step-2, see following slides
- Fermilab based experiment?
 - Well-developed proposals exist
 - Could be enabled by planned upgrades to Fermilab accelerator complex

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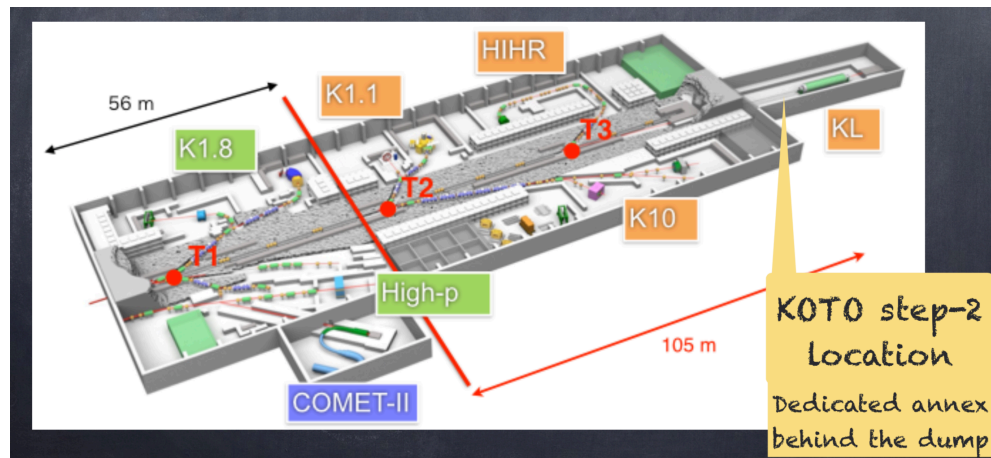
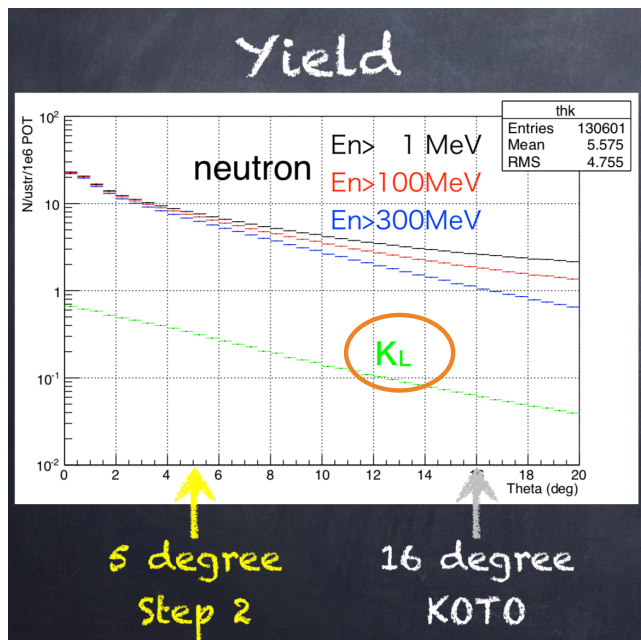


Potential Snowmass message from Rare & Precision Frontier:
design FNAL upgrades to facilitate a broad physics program

KOTO STEP-2

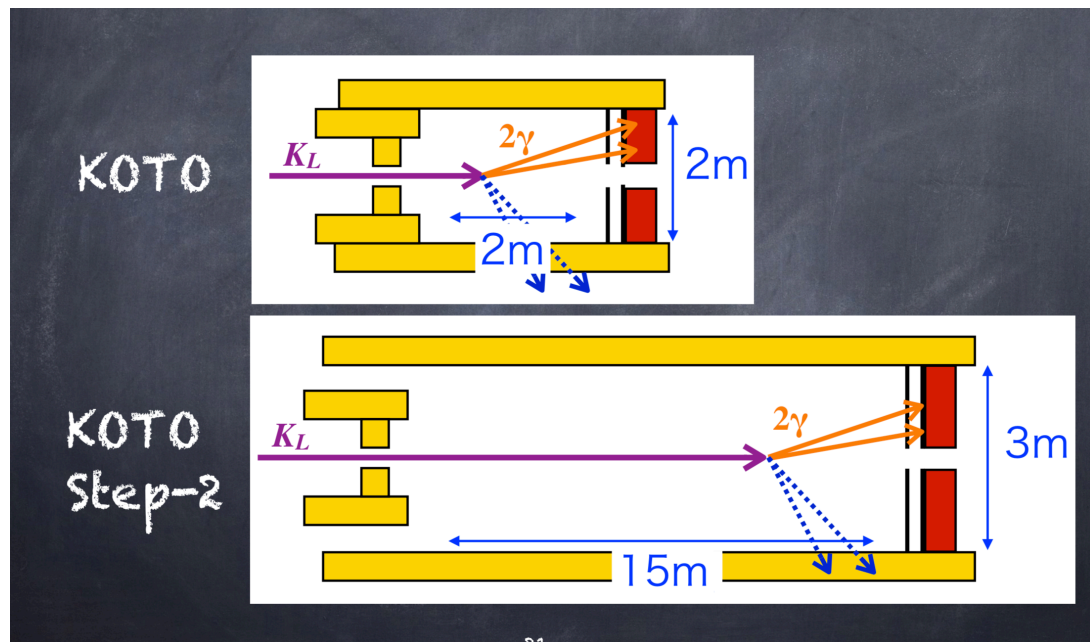
- Current KOTO (Step-1) experiment expects to reach SM SES by 2025
- KOTO Step-2 could begin construction around 2025 and observe order 100 events at SM level with signal to background ratio of ~ 1 (3 years data)
- Two major upgrades for KOTO Step-2:
 - Higher kaon flux: reduce targeting angle from 16 degrees to 5 degrees, increase target length from 60 mm to 102 mm
 - Increase detector acceptance: increase calorimeter radius from 2 m to 3 m, increase fiducial region from 2 m to ~ 15 m

INCREASE KAON FLUX



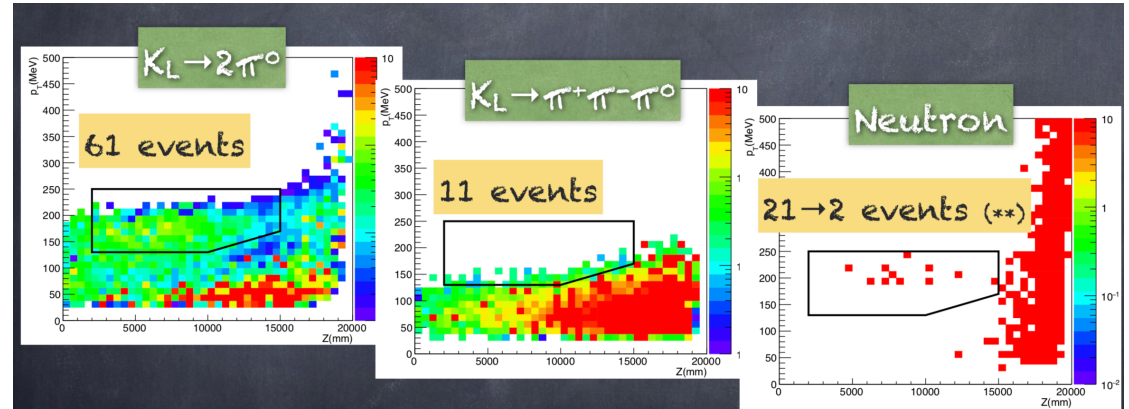
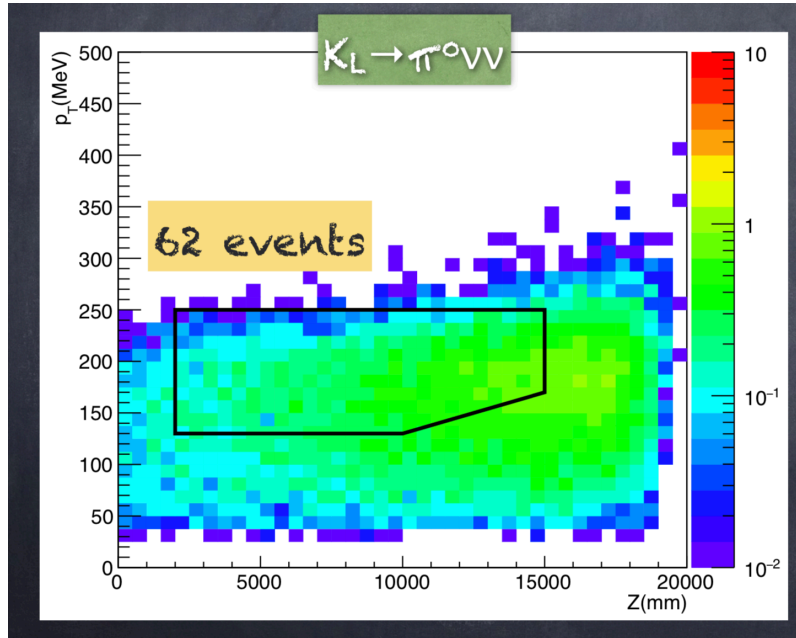
Hadron hall extension is a joint project with the nuclear physics community and is on the list of future KEK large-scale projects

INCREASE DETECTOR ACCEPTANCE



- Current endcap detector is CSI calorimeter
- Cylindrical barrel veto surrounds decay region
- Could consider detecting/measuring photons in the barrel
- Design studies ongoing

PRELIMINARY SENSITIVITY STUDY



See presentation by Tadashi Nomura at KAON 2019
<https://indico.cern.ch/event/769729/contributions/3511089>
 for details of the study

STATUS OF US INVOLVEMENT IN KAON PHYSICS

- Long history of kaon physics experiments at FNAL and BNL – most recently E787/949 and KTeV
 - First observation of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, discovery of direct CP violation, rich physics program producing many papers and many PhDs
- A few US physicists are involved in NA62; several US groups play major roles in KOTO
- BNL has been collaborating with KOTO at a low level and received some support from the US-Japan program to investigate potential BNL contributions to KOTO computing and KOTO Step-2
- ETW editorial comments:
 - The last P5 report had positive words about ORKA, both in terms of the scientific potential and the contributions to the breadth of the US program and the training of young scientists, but declined to recommend moving forward due to presumed budgetary and priority constraints. Perhaps the climate is somewhat different this time?
 - A positive statement from P5 about US participation in the CERN and JPARC experiments would be extremely helpful in providing viable paths for interested US scientists to contribute to these experiments and would help preserve the possibility of future US kaon experiments.

SUMMARY

- **Message from KOTO Step-2 LOI:** Significant experience in control of backgrounds has been acquired in KOTO Step-1 and SES at the SM level is possible by 2025. Plans for KOTO Step-2 are underway. Preliminary studies suggest order 100 events with $S/N \sim 1$ are possible. Expansion for Step-2 requires commensurate expansion of the KOTO collaboration.
- **Message from US Kaon LOI:** Both out of intellectual interest and a desire to maintain breadth in the US physics program, the US kaon physics community would like to explore possibilities for expanded US participation in the current and next-generation rare kaon decay experiments at JPARC and CERN. We would also like to hold open the possibility for more major contributions to these experiments or for a complementary US-based experiment if the science points in that direction.